Inspection and evaluation of existing structures: a task for brave engineers

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ABSTRACT: Assessing an existing structure implies its in-depth understanding. In the world of Medicine, full understanding of the patient is based on a well studied clinical history, a visual check, analytical tests and, consequently, a comprehensive diagnosis of the causes of the diseases. There is no reason not to apply a similar *modus operandi* to existing structures. This paper claims for a better education of young engineers, to enable them to understand an existing structure as a part of a fascinating whole and not merely as a mathematical model.

1 INTRODUCTION

Le Corbusier conceived Architecture as 'a wise, concrete and magnificent combination of volumes grouped under light', implicitly supposing eternal or, at least, sufficient life for them. Fernández-Casado (1975) qualified such an assertion in the sense that 'it is not a matter of volumes, but masses that weigh and resist; the architecture of engineers is rooted in a cosmic vision, forcing them to an ascetic attitude in relation to Nature, to stoical withstand the attraction of superfluousness; a non-timeless attitude, independent of momentary tendencies'.

Figure 1. Le Corbusier and Fernández-Casado. Two different but complementary visions of the structures of 20th century.

During the last fifteen years, a new concept is present in the basis of design of engineers, together with safety against failure and an adequate serviceability: durability. Modern standards, as the Spanish Concrete Code EHE (1998), state: 'A structure must be designed and erected in such a way that it can resist all corresponding actions both during construction and along the lifetime foreseen in design, with acceptable safety, as well as environmental aggressiveness'. To ensure durability, a fourth aspect is gaining importance in engineering practice: maintenance. The oncoming edition of the Spanish Concrete Code EHE (2008) already includes this idea: 'Maintenance can be defined as the set of actions necessary to ensure that the features of a structure, as a basis of design, do not fall below a certain threshold value along its lifespan. This threshold value is related to the strength, durability, functionality and even aesthetics'.

Certain established attitudes defended the idea that structures should not be in service beyond a nominal lifetime, independently of the condition of the structure, and then replaced. However, the increasingly present sustainable principles are pushing towards new strategies of decision, including the possibility of enlarging the service life of existing structures. Indeed, little attention has been paid to the structural maintenance, from the technical, economical and educational points of view, which is also a symptom that society has not considered structural maintenance as important as the maintenance of aircrafts or high speed trains. Unfortunately, due to some accidents, it seems that this tendency is changing (figure 2).

The opinion of the authors is that this new attitude opens new possibilities and challenges for engineers, but also new requirements regarding their skills and education. This paper tries to shed light on this topic.

Figure 2. Collapse of the bridge over the Mississippi River in Minneapolis (August 1st, 2007).

The need of maintenance involves structures of all ages, materials and typologies (figure 3), requiring, as Poul Beckman (2004) says, 'a couple of open eyes and an open mind', which means an overall knowledge and expertise in structural engineering. It is also worthwhile mentioning that, once again, the experience gained in the field of structural concrete has settled the basis for a general and comprehensive treatment of this problem.

Figure 3. Degradation processes affect a great variety of structures and condition, always increasing with age.

2 THE 'LIFE-CYCLE' CONCEPT

Figure 4 shows the evolution of the life expectancy in Spain over the last 108 years. It is evident how the application of preventive measures and an adequate sanitary policy ('maintenance') has practically doubled this expectancy. There is no reason to think that an adequate maintenance policy, applied to the existing structures, can not lead to an enlarged, engineer based, life of the structures. Figure 5 shows a summarized but clarifying chart of the life process of a structure, paralleling to the one of a human being, and the related attitude of engineers.

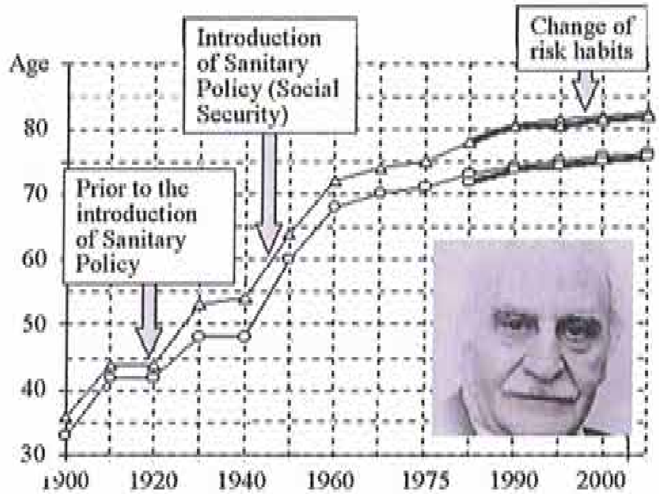

Figure 4. Evolution of life-expectancy in Spain and an example of increasingly more frequent exceptions: the writer Francisco Ayala, 102 years old and still active.

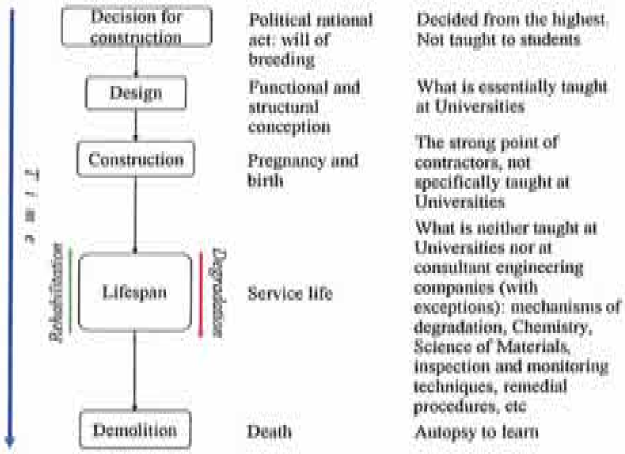

Figure 5. The life cycle and the frame of tasks of inspection and maintenance.

Although in this figure the first step, the decision for construction, is usually outside of the scope of a technician, it is also very useful for him to know about the historical circumstances of such a decision. A skilled technical inspector can extract a lot of information from the history of construction: regulatory guidelines on actions, quality of materials used (strength and durability properties), methods of construction, etc.

In any case, both design and construction take few months, a relatively reduced time compared to the long and usually forgotten period of service. However, the inexorable degradation of materials, some design mistakes or construction defaults, condition the lifetime of the structures. The knowledge of all these causes could help to improve the processes of design and construction and, as a consequence, it seems clear that the inspector engineers can give important feed-back information. Nevertheless, the truth is that the biggest part of the effort of universities and other training institutions, e.g. engineering companies, has been devoted to project. In this regard, designing engineers are assisted by standards or procedures, which make easy their task and reduce the responsibility of the technicians. Although it seems rather unfair and probably excessive, it does not matter if the engineer understands what he is doing; the important thing is that he is under the comfortable umbrella of a standard.

3 INTERPRETING DAMAGES

There are several classification catalogues (León et al. 2003) of damages available for technicians. The problem is that excessive task specialization unfortunately has led to a situation of only partial understanding and even misuse of such documents. Thus, on one hand, specialists on structures feel happy when dealing with structural diseases (i.e. cracking due to shear or bending, etc.), but, on the other hand, they become uncomfortable when they have to understand the electrochemical process of steel corrosion or the sulphate attack on concrete. On the contrary, when chemists are called to inspect a construction showing structural problems, they tend to discover corrosion processes, although the cause is quite simple (e.g. cracking due to overloading, not foreseen for modern live loads, or originally produced during construction). Therefore, it may be concluded that interpreting damages requires 'complete' technicians, that is, engineers who are well trained and educated, in cooperation, of course, with many other specialists. The following are just few examples of these ideas.

Figure 6. Settlement: a relatively easy symptom to qualify.

It is well known that structural movements (figure 6) induce, it is well known, reduced consequences in statically determined structures and, in theory, more important ones in statically undetermined structures. The structural engineer must be aware that even the latter may be less important than derived after a classical, conventional, but untrue, elastic analysis, provided that they were designed with sufficient ductility (this amount of ductility has not been quantified yet as a function of the imposed displacement).

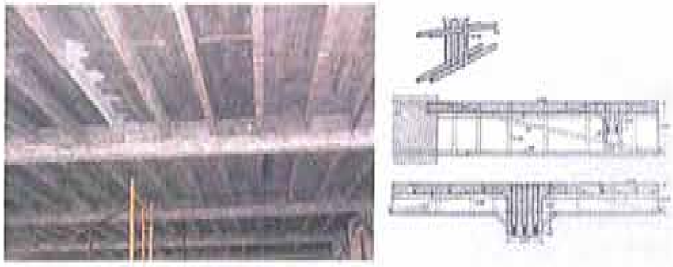

Figure 7. Apparent sound old structures: a potential trap.

Figure 8. Diagonal cracks announcing a compressed strut.

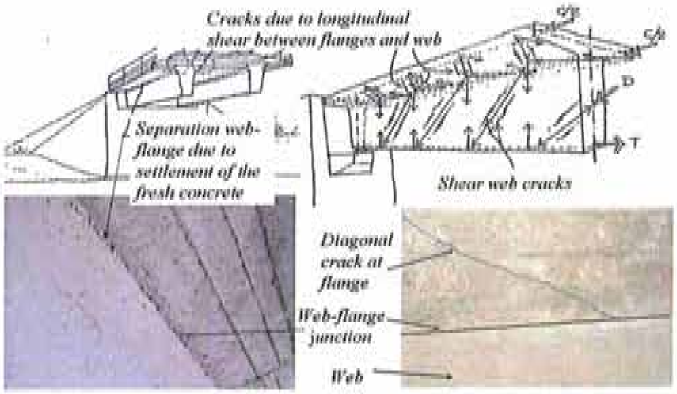

Figure 9. Misunderstanding of web top part separation in relation to the flange, and cracks due to longitudinal shear.

At the other extreme, the engineer may find structures, with no cracking patterns, although with big delayed deformations. Designed in the early times of structural concrete, when the concepts or arranging steel bars on the compression zones were not clear yet, this type of structures may be rather brittle and admit no repair techniques by means of the always promising techniques of carbon fiber strips. In spite of their good appearance, these structures hide their poor condition and might be a real trap to an unaware inspector (figure 7).

In front of a diagonal crack (figure 8), the inspector who had to study structural concrete (or, even better, teaches it nowadays), feels the ineffable sensation of identifying real strut-and-tie models, which seemed rather arbitrary simplifications of textbooks. From the point of view of durability, it is not yet clear why, even under aggressive environmental conditions and with crack widths beyond the conventional limits, there is no higher level of corrosion in these zones than in other, even uncracked ones.

Figure 9 shows a specific case of confusion between the consequence of differential settlement of fresh concrete mass of the webs with respect to the flanges and the effects of longitudinal shear between flanges and webs. It is not uncommon to find reports recommending strengthening webs and flanges with transverse reinforcement.

Some inspectors feel frightened when they discover large but single cracks on masonry or plain concrete vaults, in crown and springing zones (figure 10). In fact, such cracks are a mere consequence of the normal functioning of the structure. However, the fear of the inspectors is justified because they do not understand the working mechanism of such structures, which are not taught at the University because this old typology is no longer used in modern design and construction. Another reason to underline the vast formation required to inspectors, much broader than supplied today at universities.

Hidden design or construction defaults may lead to situations of collapse as shown in figure 11. Surprisingly, in this case the architect decided to repair the structure. Indeed, there are modern techniques to rehabilitate columns by means of new confined concrete covers, but a sensible engineer must establish a logical limit to the repairability, closely related to the importance of the damages, the costs of repair and the remaining lifespan.

De-icing salts, in zones of continuous low temperatures, may produce important damages to concrete, threatening even the stability of bearing devices, as shown in figure 12. The problem is especially important in zones of water leakage, i.e. in joints, and could be avoided by means of simple devices to keep the water off. The authors wish to express at this stage the rewarding experience gained when inspecting structures abroad, in zones with climates and engineering traditions different from own's.

Chemical attacks are not easily identified, since similarl symptoms may have radically different origins (figure 13). Thus, plastic shrinkage shortly after casting concrete, thermal effects also during the hardening process of the cement paste, or chemical attacks due to water with sulphates produce cracking with the same appearance. The capability of the inspector on the site is essential to properly identify the most probable cause (or causes) of the problems he comes across and to prescribe the complementary analyses and remedies.

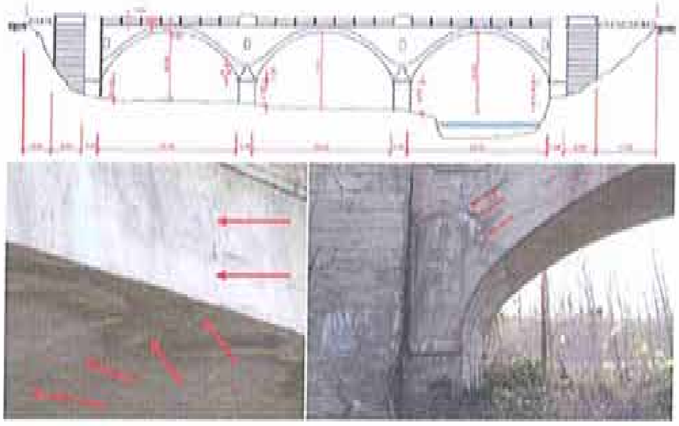

Figure 10. Normal, harmless cracks, showing normal behaviour, although alarming to an inexperienced technician.

Figure 11. Collapsed column of a building with durability problems as well as poor design of details and construction.

Figure 12. Effects of de-icing salts. It is normally believed that salt=chlorides=corrosion of reinforcement, but it is even worse, in extreme weather conditions, the effect of the local freezing-thaw, producing scaling of concrete.

Figure 13. The coincidence of symptoms with different origins calls the attention specifically of well trained inspectors.

In recent years corrosion processes have been studied in depth, providing models that supply a reasonable good estimation of structural lifespan (figure 14). By means of these models, the engineer is able to evaluate the residual lifespan and to design the eventual repair procedure. This last activity is still considered a minor task, but implies a great responsibility, since a badly conceived or executed repair may disguise other real diseases and, therefore, shorten the life of the repaired structure.

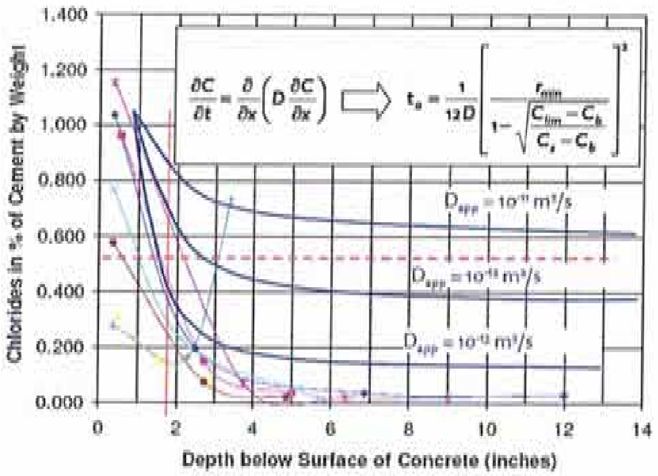

Figure 14. Available model, based on Fick's second law, to predict the initiation period of the corrosion process of re-bars.

4 MAINTENANCE ENGINEERING

Once accepted that structures suffer inexorable degradation processes, the task of engineers is to define the most suitable strategy to maintain their safety, functionality and durability. Figure 15 shows a diagram of Prof. Mola (1997), summarizing the elements of the eternal fight against failure. Every repair operation leads, if well directed, to an increasing of the lifespan.

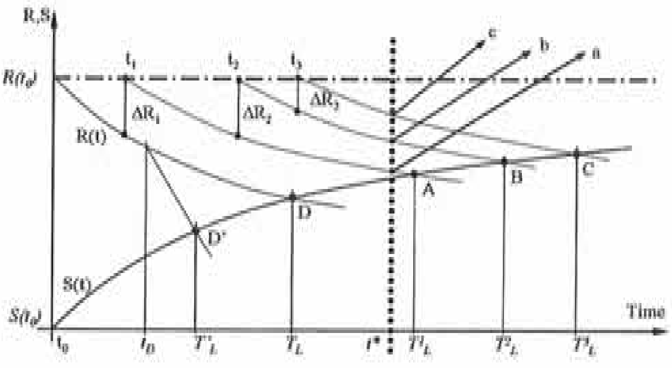

Figure 15. Evolution of actions $S_d(t)$ and capacities of the structure $R_d(t)$. Possible interventions to increase the lifetime.

Figure 16 shows the same ideas on a variation of the classical diagram of Tuutti (1982). Lifespan t_1 of the structure is the sum of both the initiation and propagation periods. The time t_2 could be understood as an 'extended' lifespan forced by the circumstances. 'Reactive' interventions (unfortunately, the most common which take place just after surpassing an acceptable or limit situation) at age t_B, lead to an increased lifespan equal to t_{1B}-t_B. Frequently, when the time of intervention is higher than t_B, the repair or strengthening operations are more expensive or even unaffordable and the structure must be replaced.

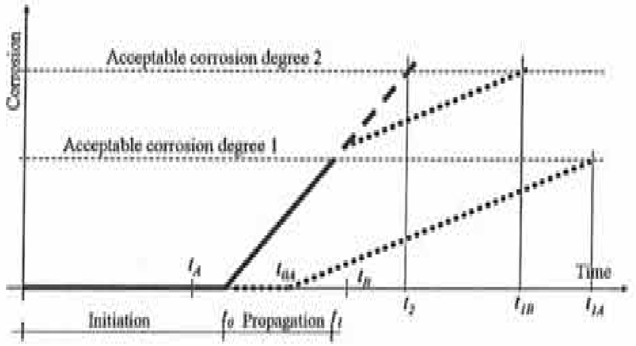

Figure 16. Variations on the classical diagram of Tuutti, expressing the predictable lifespan and how to enlarge it by means of timely intelligent interventions.

Figure 16 also shows how the success of an intervention may be much more profitable if a 'proactive' intervention is adequately programmed. The closer, but not later, to the end of the initiation period and the more effective intervention (with the smallest slope of the damage evolution), the most durable (and probably cheaper) solution shall be obtained. When intervening at time t_A, it is possible to delay t_0 until t_{0A} and the propagation period, till t_{1A} is also enlarged, even for a more strict accepted level of corrosion. The quantification of the end of both the initiation period and the propagation periods requires a correct diagnosis of the degradation mechanisms and a correct evaluation of the relevant parameters of the available models: again a task requiring expert engineers.

It is very interesting to detect that some societies have assumed the need of a maintenance policy, as in the case of the Mosque of Djanné, in Mali (figure 17). Whenever necessary, the citizens are requested to make a personal effort to repair the old mudwalls.

This is an admirable example of 'proactive' intervention. The example goes beyond that, since horizontal protruding logs, permanently attached to the walls, serve as auxiliary elements to allow people to climb up and carry out the operations of inspection and maintenance. Auxiliary devices for this purpose are required by new Standards, i.e. the new Spanish Code for Structural Concrete.

In recent times, a complementary concept of safety is growing and affecting engineers: the user's safety. It is not only a matter of torsional cracks or chloride contents, that is, the security of the structure itself, but something more concrete to the citizen and to the politicians: it results unacceptable (political and economically expensive) that structures or their equipment might become dangerous to users in case of foreseeable accidents (figure 18). The question is located in a not well defined frontier: it belongs neither to the structural engineer nor to the expert in bridge railings. It is worth to mention that the problem is of tremendous complexity and that the common way of solving it is empirical, by means of tests, leading to empirical proposals that are valid for a given set of circumstances.

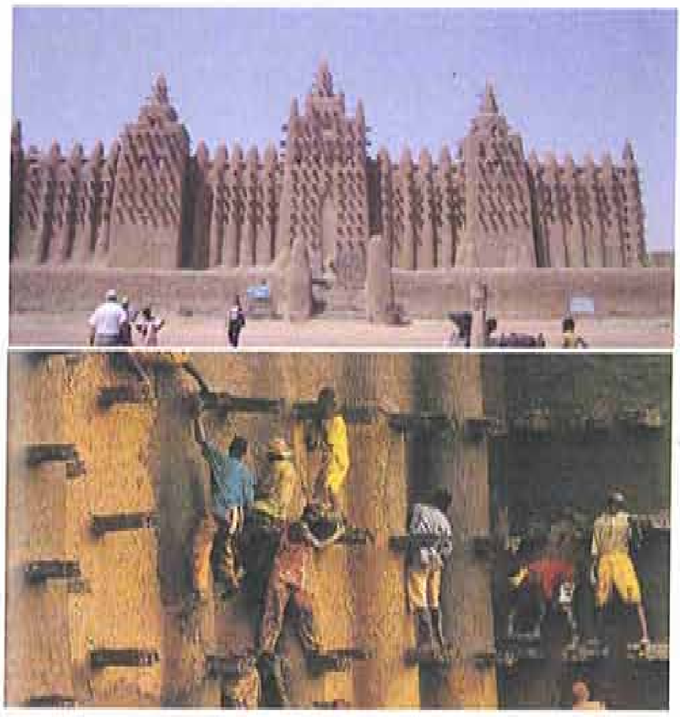

Figure 17. The Mosque of Djanné (Mali).

Figure 18. Railings: a topic that relates user's safety and structural aspects.

5 EDUCATION

The need for housing and infrastructures has conditioned the professional profile of the current engineers, directed only towards new structures. Besides, young engineers seem to be rather 'blinded' by the new and huge bridges, buildings or facilities, symbols of prestige and social success. But once such constructions start showing defaults, it becomes essential to inspect them to valuate their condition and intervene in the most intelligent possible way. This task requires trully interested, well trained and brave engineers, capable to accept the challenge of this fascinating field of the professional activity.

Universities must complete their educational offer including a sufficient formation of such disciplines related to Structural Analysis, involving all kind of structural materials, typologies, ages or functions, but also Chemistry, Science of Materials, Non Destructive Techniques of inspection and monitoring and even Linguistics and Terminology (Bauder, 2007). It is the right time now to mention such a need, at least in Europe, where a new 'space of common education' tries, theoretically, to offer to the society the required professionals. To teach students it becomes necessary to stimulate the participation of professional engineers in the teaching process, as medical doctors teach at faculties and hospitals, at the open air of reality, bringing also the freshness of the relation that such activity has with history, politics, economics, art, etc. This approach will also contribute to cure the 'blind calculism', an illness affecting young engineers that believe that their professional activity consist in conceiving the world through powerful, coloured but even vain finite element models.

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